Electricity Grid

Impacts of Plug-In Electric Vehicle Charging

by Christopher Yang and Ryan McCarthy

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Concerns regarding air pollution, energy dependence, and, increasingly, climate change continue to motivate the search for new transportation solutions. Much of the focus is on light-duty vehicles, as they account for approximately 60% of transportation energy use and greenhouse gas (GHG) emissions. Battery-powered, electric-drive vehicles (EVs), such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), are among the most promising of the advanced vehicle and fuel options that have been proposed to help reduce fuel usage and GHG emissions from light-duty vehicles.

PHEVs are like conventional hybrids in that they can be powered by either gasoline or electricity, but unlike hybrids, PHEVs can be plugged in to obtain some of their energy from the electric power grid. The use of electricity as a fuel in these vehicles can dramatically reduce GHG emissions because of the inherent efficiency of electric drivetrains, as well as the potential to use very low-carbon electricity resources, such as renewables.

While the success of these "plug-in" vehicles largely hinges on the development of robust, low-cost batteries, the fuel side of the equation is equally important to consider. A number of questions still need to be answered about the ability of the grid to handle the additional demand, and the costs and emissions associated with charging these vehicles. This article discusses how electricity demands for vehicle charging can interact with the electricity grid and how costs and emissions depend on the quantity, location, and timing of vehicle electricity demands.

The Electricity Grid

The electricity grid is a collection of power plants and transmission and distribution facilities that produces and delivers electricity to end users. It must do so in real-time, because electricity cannot be practically stored in significant quantities. The grid has evolved to meet continually changing electricity demands by using a suite of power plants that fulfill various roles in the grid network.

Each type of power plant operates differently, and can be a different size and employ different technologies and resources, and as a result, each has unique cost and emissions characteristics. Baseload facilities, often large coal or nuclear plants, are designed to operate continuously and at low cost. Peaking power plants, which are operated only a handful of hours per year when demand is highest, are often fired with natural gas or oil, and are more costly to operate. Many other types of plants operate in between. The mix of power plants that make up the grid will vary significantly from one region to another—based on local demand profiles, resource availability and cost, and energy policy.

While fossil fuels (mainly coal and natural gas) provide 70% of U.S. electricity generation, the grid is evolving as the level of renewable generation increases. More than half of U.S. states and several European countries have a renewable portfolio standard (RPS), which mandates renewably-based electricity generation. However, these renewable resources are limited in resource quantity, temporal availability, and reliability. Intermittent renewables, such as solar and wind, can pose additional challenges associated with integration into the grid.

Because of the structure of the grid, the cost of electricity and the emissions associated with generation will vary with demand and power plant availability. Charging an electric vehicle requires the grid to respond by providing more electricity. A key consideration for understanding the cost and emissions implications of plug-in vehicles is how the grid system responds to the additional demand.

Plug-In Electric Vehicles

Vehicle recharging will impact the grid in both the immediate and long term. In the near term, recharging vehicles will require additional electricity to be generated. However, it will take a very large number of plug-in vehicles in a region before power plants are operated differently or new ones are needed. For example, adding 1 million PHEVs in California (out of 26 million vehicles) only increases total electricity consumption in the state by approximately 1%. If that increase occurs off-peak, no new capacity is likely needed.

Over time, as greater numbers of plug-in vehicles are introduced, their influence on the structure and operation of the grid, and resulting cost and emissions impacts, will become more important. This depends on the quantity and timing of vehicle electricity demand. As the number of vehicles and their electricity requirements increase, more power plants are operated in the present, and will be built in the future. If each of the 240 million registered vehicles in the United States charged 5–10 kWh per day, this would require an additional 12–23% electricity generation. However, assuming that most vehicles will charge overnight, the requirements for additional generation capacity would most likely be much lower. The spatial and temporal pattern of charging can ultimately influence the total generation capacity, the mix of power plants serving a region, and their cost and emissions. The spatial pattern of charging can influence the distribution system, as well.

Vehicle Emissions and Costs

Environmental impacts from conventional and advanced vehicles and fuels need to be analyzed on a "well-to-wheels," or life-cycle, basis to fully account for their operational differences. Well-to-wheels emissions include those associated with the production and transport of the fuel to the vehicle (i.e., "well-to-tank") and those associated with fuel conversion in the vehicle (i.e., "tank-to-wheels"). Emissions from internal combustion engine vehicles are predominantly tank-to-wheels, but for EVs, the well-to-tank (e.g., the generation of electricity) comprises the majority of emissions.

Table 1. Energy and carbon intensity values for conventional vehicles, hybrids, and PHEVs.

	Vehicle Energy Intensity (E)		**Fuel Carbon Intensity (C)**		**Vehicle Carbon Intensity (ExC)**
	MPGGE	kWh/mi	gCO$_2$/gge	gCO$_2$/kWh	gCO$_2$/mi
Conventional Gasoline	27.5	1.21	10,997	330	400
Hybrids / PHEVs in "hybrid mode"	40	0.84	10,997	330	277
BEVs / PHEVs in "all electric mode"	111	0.3			
Renewable electricity			0	0	0
Natural gas combined cycle			13,300	400	120
Avg. CA electricity			14,000	432	130
Avg. U.S. electricity			20,333	610	183
Coal steam			39,600	1188	356

Thus, for vehicles that plug into the grid, characterizing the emissions associated with electricity generation and distribution is important for understanding the environmental impacts of the vehicles. This requires an understanding of which power plants are operating during vehicle recharging that would not be generating power otherwise, also known as marginal generation. The marginal generation will typically be the easily controlled (i.e., dispatchable) power plants, but they are also the most expensive, and often least efficient, plants operating at the time. Consequently, the GHG emissions rate from these power plants (i.e., the marginal rate) often differs significantly from the emissions rate from all of the plants operating at a given time (i.e., the average rate).

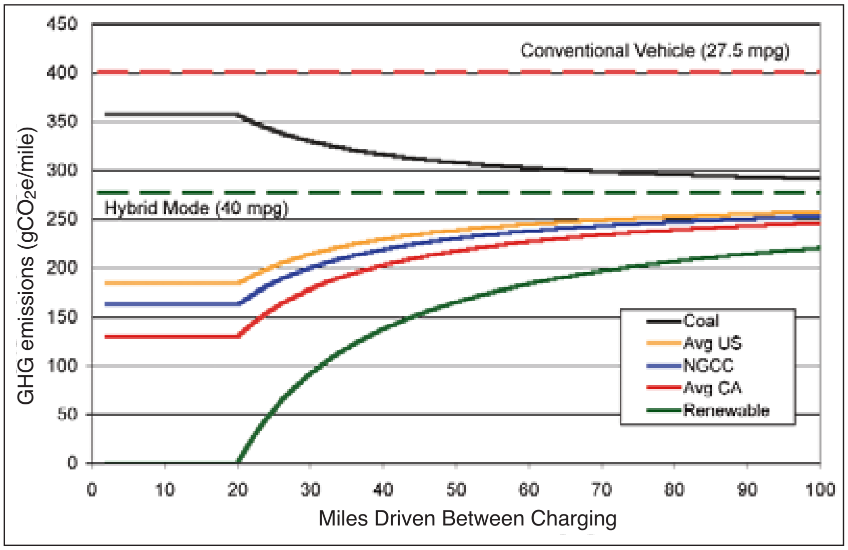

Figure 1. *Representative GHG emissions for a PHEV20 operating on different electricity sources and recharging intervals.*

Table 1 shows some representative numbers for the energy intensity (energy/mile), fuel carbon intensity (carbon/unit energy) and their product, and vehicle carbon intensity (carbon/mile) for conventional vehicles, hybrids, and PHEVs in charge sustaining "hybrid mode" and EVs and PHEVs in "all electric mode."

Emissions attributable to plug-in vehicles depend on the regional characteristics of the grid and the magnitude and timing of demand. A commonly held assumption is that vehicle recharging is likely to occur at night, during off-peak hours, because that is when most cars are parked at home. However, if coal power plants (~1000 gCO$_2$/kWh) provide marginal generation for off-peak vehicle demands, GHG emissions from plug-in vehicles could be higher than emissions from hybrid vehicles. However, if natural gas-fired power plants (~400–600 gCO$_2$/kWh) operate on the margin, which is often the case, well-to-wheel GHG emissions from plug-in vehicles will be lower than those from conventional hybrids, and considerably lower than those from conventional vehicles. The exact emissions comparison will depend on the vehicle design (i.e., BEV vs. PHEV), the efficiency of a conventional vehicle, and how the vehicles are driven.

PHEVs will typically combine all-electric and hybrid modes, as shown in Figure 1. Most of the curves in Figure 1 assume a PHEV with 20 miles of all electric range (PHEV20) that operates in all electric mode for the first 20 miles and then operates in hybrid mode thereafter. If this vehicle were driven 50 miles between recharging, it would operate 20 miles on electricity and 30 miles on gasoline and the GHG emissions per mile

would be a combination of the emissions in each mode. As the distance a vehicle is operated between recharging the battery increases, the GHG emission per mile asymptotes toward the emissions associated with hybrid mode operation. A BEV would operate in all electric mode for the entire vehicle range rather than only 20 miles.

Infrastructure Impacts

Several studies show that existing grid capacity (including generation, transmission, and distribution) can fuel a significant number of PHEVs in the U.S. light-duty vehicle fleet.[1] Many power plants are underutilized during off-peak hours and could be used to recharge a majority of vehicles in many areas of the United States. Studies have indicated that the transmission and distribution infrastructure that transports electricity to the end user will, in most cases, not be overburdened by charging vehicles, either.

But there may be specific points along some distribution lines that face congestion if local patterns of electricity demand change significantly because of vehicle recharging. At the substation and feeder levels, where demands are less aggregated—and as a result, more variable and sensitive to the patterns of a few customers—distribution impacts are important. If many consumers in a given circuit recharge their plug-in vehicles simultaneously (e.g., in the early evening after work), it could increase peak demand locally and require utilities to upgrade the distribution infrastructure. Utilities may want to manage the timing of recharging demand to maximize load factors and utilization of existing distribution resources. Typical U.S. households consumed approximately 11,000 kWh annually in 2001. The addition of a PHEV with 5–10 kWh of useable battery capacity that is charged once per day could add an additional 21–43% (2200–4600 kWh) per year to the household electricity load, comparable to average central air conditioning and refrigeration loads.

The mix of power plants supplying a region is largely a function of peak demand and the hourly demand profile. Peak demand determines the total installed power plant capacity needed to supply a region, while the hourly demand profile determines the best mix of plants. Based upon the pattern of demand over the year, the economically-optimal mix of baseload, intermediate, and peaking power plants can be determined. As a result, if vehicle electricity demand adds to peak demands, it may require the expansion of existing grid capacity and building new infrastructure. Or, by changing the hourly demand profile, it may affect the generation mix. Charging off-peak will flatten the demand profile, thus improving the economics of baseload and intermediate power plants and lowering average electricity costs. Charging at peak demand times will increase capacity requirements, while lowering the utilization of existing plants and increasing electricity costs.

Timing is crucial in determining whether electric plug-in vehicles are a benefit or detriment to the grid.

Plug-In Vehicles as 'Active Loads'

The grid will adapt to meet the demand for vehicle charging, as it does for all demands. However, plug-in vehicles may be unique, if charging can be controlled to occur when it is most optimal. Given that cars are parked approximately 95% of the time, this is a real possibility.

One model for understanding how plug-in vehicles can impact the electricity grid is based upon the concept of "passive" and "active" grid elements (e.g., generators and loads). Passive elements are imposed on the system and do not readily respond to grid conditions. Active elements can be controlled and utilized when optimal. Baseload and intermittent generators are passive, since they cannot easily turn on or off, or up or down, in response to changes in demand. Active generators can be operated to follow or match demand. Most electricity demand is passive, as it is imposed instantaneously on the electric system by millions of individual customers and not easily controlled. But electricity demand for some loads, including plug-in vehicles, can be active. The timing of recharging demand is controllable, because energy is stored onboard the vehicle in batteries, and vehicle travel is temporally separate from the time when recharging occurs.

The grid manages active and passive elements in real-time to match supply and demand. Traditionally, the grid has consisted of passive electric demands, which requires precise matching by active generation, such as dispatchable natural gas power plants. But active loads, such as those from plug-in vehicles, may be used to match passive elements, potentially reducing the need for active generation.

Additionally, plug-in vehicles can enable the deployment of intermittent renewable generators, such as wind or solar. Since these passive generators are highly variable, they must be matched by standby active generation, typically natural gas-fired generators that are utilized when the renewable resource is unavailable. But aggregated active loads from plug-in vehicles could also be used, potentially reducing the required number of standby power plants and decreasing the costs associated with integrating intermittent power on the grid.

Managing Vehicle Recharging

Clearly, timing is crucial in determining whether these vehicles are a benefit or detriment to the grid. Many utilities and policy-makers already recognize this, and strategies are being developed to educate consumers.

Managing vehicle recharging requires a smart charging system that enables communication between the customer and utilities. This enables the utility to manage customer charging patterns, and participating customers may receive lower rates and maximize the amount of renewable electricity they purchase. This charging interface can also permit vehicle charging emissions to be appropriately tracked and allocated, which will become increasingly important as states and countries adopt low-carbon fuel standards and impose caps on GHG emissions in different sectors.

While recharging vehicles during off-peak hours is preferable from a grid operations and cost perspective, off-peak recharging may not always be preferable to all stakeholders. For example, a consumer may be able to avoid a trip to the gas station by recharging during the day, and though this may be more costly than charging off-peak (the cost of peak electricity can be a factor of three or more higher than off-peak power), it may still be cheaper and less polluting than operating the vehicle on gasoline. Some companies may even incentivize daytime recharging by offering recharging stations at the workplace or around town.

Conclusion

Plug-in vehicles offer environmental and energy security benefits for light-duty transportation. But it is important to consider these benefits in terms of how new electricity demand for vehicle charging impacts the grid. Ultimately, plug-in vehicles present a great opportunity to diversify energy supply and reduce transportation environmental impacts. But they must be considered in the context of regional grid structure and operations, and the appropriate technology and policy incentives should be implemented to maximize benefit. **em**

Reference

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